

SHORT-PERIOD SURFACE WAVES FROM EXPLOSIONS

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ABSTRACT

We have examined the generation and propagation of short-period (0.5- to 12-sec period) surface waves from different classifications of explosions. A dataset of local and regional recordings of single-fired chemical explosions (Non-Proliferation Experiment and Balapan Depth of Burial shots), coal-mining explosions (including cast and coal shots from northern Arizona), rock fragmentation shots (SW Arizona), and quarry blasts (Central Texas) has been assembled. The dataset has been complemented with detailed source parameters including origin times, shot patterns, and additional information key to modeling the physics of the various explosions. We are currently completing the initial phases of this project that included database compilation, observational studies, and preliminary modeling of the explosions. During the next phase of the project, we propose to expand on the modeling effort to include complex source models and propagation in 3-D media using Fourier pseudo-spectral approximation (Orrey *et al.*, 2001).

The initial focus has been on the modeling of surface-wave generation from two cast blasts of similar yield (~1.6 million pounds ANFO), delay sequence, and near-source structure at a coal mine in northern Arizona. The shots were oriented approximately perpendicular to each other, allowing for interesting comparisons at both local and regional distances. Near-source data (< 5 km) collected by Southern Methodist University and Los Alamos National Laboratory show the dominant surface-wave energy is delayed with respect to the blast initiation time and is better aligned with the onset of horizontal spall impact. Surface wave amplitudes recorded for both shots at regional distances differ by as much as a factor of 2.5, and these differences can be attributed to the orientation of the casting. To test this theory, we completed a preliminary modeling study to investigate the source of the azimuthal radiation patterns using the detailed blasting information obtained from blast engineers and MineSeis1.1 (Yang, 1998). The radiation patterns generated for the blasts were not isotropic as is the case when only vertical spall is modeled, and show larger amplitude lobes perpendicular to the bench, with a small amplitude increase noted for the direction of the delay firing. The overall effect of the horizontal spall is to create amplitudes as much as four times greater in the direction normal to the bench than parallel to the free face. These modeling results support our regional observations. Since equivalent radiation patterns were not observed for the *P* and *Lg* phases, the observation of these radiation patterns at regional distances could act as a cast blast discriminant in regions of monitoring concern.

KEY WORDS: mining explosions, surface waves, discrimination

OBJECTIVES

Introduction

Previous studies have shown that a significant number of small regionally recorded seismic events are mining explosions (Richards *et al.*, 1992; Sorrells *et al.*, 1997; Leith *et al.*, 1996; and Khalturin *et al.*, 1996).

Unfortunately, few, if any, validated discriminants exist for any of the wide variety of mine explosions that occur in numerous mining areas, many of which are in regions of high monitoring interest. The objective of this research is to determine if there are unique aspects of short-period (0.2 to 12 seconds) surface wave

generation by mining explosions that will aid in the development of transportable regional discriminants. To complete this goal, we have:

- Collected regional seismic data to examine short-period (0.5 to 12 sec) surface wave generation from different types of chemical explosions in North America and Kazakhstan.
- Determined the propagation characteristics for short-period surface waves generated by explosions in different tectonic settings, and
- Determined additional features unique to surface waves from mining explosions that can be used in the development of a regional discriminant.

In the following sections, we will present results that show the feasibility of modeling explosions of varying classifications in different source regimes using the explosion-generated surface wave datasets.

RESEARCH ACCOMPLISHED

Data Collection

We have collected different data sets to study surface wave generation from different classifications of small explosions, including delay fired mining explosions (cast blasts, quarry blasts, and fragmentation shots) and simultaneously detonated explosions. Table I provides details about the data collected thus far and anticipated datasets that will be acquired shortly. The sources are located in different

Experiment	Explosion	Data Collection
Balapan	Single-fired chemical	9 shots ranging from 25 to 0.1 tons at depths from 2.5 to 550 m. Close-in LANL data from 78 stations. Regional data from the Kazakhstan network.
NPE	Single-fired chemical	1 1.07 kt shot at the Nevada Test Site. Regional data from Sandia Net and a University of Arizona Profile. We will also obtain LLNL network data and the Cambridge Univ. profile of seismic stations in upcoming months.
Northern Arizona	Cast Blasts	2 1.5 million pound shots from a coal mine in Arizona. Close-in network (8 stations) and regional recordings (14 stations) ranging from 100 to 700 km. Additional recordings of overburden, parting, cast, and coal shots with blasting parameters.
Arizona	Fragmentation	Copper mining explosions recorded at Tucson (TUC) and other regional stations. Received blasting parameters too late for inclusion in proposal
Indiana	Cast Blasts	Surface waves recorded from coal mining explosions at regional distances by the Billiken network. Currently acquiring source information.
Central Texas	Quarry Blasts	Previous research on azimuthal variation of R_g energy from quarry blasts.

Table I. Database of short-period surface wave explosions.

tectonic regimes, ranging from stable continental crust (Central Texas, Indiana, and Balapan) to complex regions such as Arizona and Nevada. The data allows for an interesting comparison of the generation and propagation of short period surface waves from explosions. In the upcoming months, we plan to continue data collection in central India and Minnesota.

Classification of Mining Explosions

Cast Blasts. Explosive casting is the technique used by many surface coal mines to control the displacement of overburden (Morhard, 1987) by means of explosive energy. The casting moves 30-80% of the overburden into the mined-out pit, while the remaining spoil is removed by draglines or other machinery. A blasting engineer must consider bench height, pit width, borehole diameter, and geologic formation when designing a cast blast. In most cases, the blaster uses a complicated sequence of downhole and surface delays to minimize the ground roll associated with the large amounts of explosives (between 0.5-8 million pounds of ANFO) used in a cast blast. An example of a cast blast from a mine in northern Arizona is shown in Figure 1. The casting of the overburden into the pit creates both horizontal and vertical spall force components that influence the generation of surface waves (Figure 1; Anandakrishnan *et al.*, 1997).

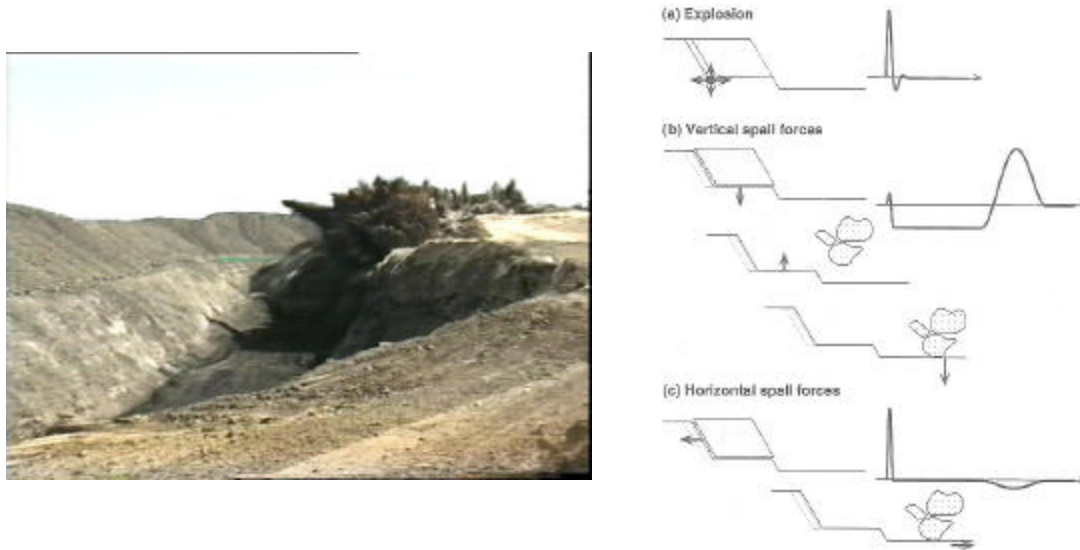


Figure 1. (Left) Cast blast in northern Arizona. (Right) Graphical illustration of the forces resulting from a cast blast into a pit (Anandakrishnan *et al.*, 1997).

Fragmentation Blasts. The majority of hard rock open-pit mines design blasts that will optimize the *in-situ* fragmentation of the material. This is accomplished by loading the holes with two different energy levels: higher energy explosives in the bottom and lower energy near the top. The result is that the material is not thrown into the mined-out pit as in the cast blasts. Instead, the material is fractured in place and removed with shovels and haul trucks. Seismic waves generated from a fragmentation blast should be influenced only by the explosion point and vertical component spall forces.

Quarry Blasts. A third type of explosion used in the mining industry is for quarrying materials such as limestone, gravels, and igneous rocks. On average, quarry blasts (Figure 2) are smaller in spatial extent and explosives content than fragmentation and cast blasts. Since these operations usually involve the crushing of the rock, efficient fragmentation of the rock into small pieces is required for use in a rock crusher. For ease in extraction of the materials, the rocks are usually blasted into the mined-out pit. Quarry blasts seismograms will thus have both horizontal and vertical spall forces effecting the regional seismograms.

Modeling Mining Explosions

We have completed a preliminary modeling study to investigate the aspects of *Rg* generation from these different classifications of mining explosions using MineSeis1.1 (Yang, 1998) and the model developed by Anandakrishnan *et al.* (1997). The model assumes the principle of linear superposition (Stump and Reinke, 1988) to handle the delay firing with the subsurface explosion modeled as a spherical isotropic point source



Figure 2. Quarry blast in central Texas.

(Mueller and Murphy, 1971). The spall model from Barker *et al.* (1993) as modified by Yang (1998) is used to model vertical and horizontal spall components. For a more detailed explanation of the model, the reader is referred to Yang (1998). For this modeling exercise, we considered a simple mining explosion with a single row of charges delay-fired to the north (0° azimuth) with horizontal spall normal to the bench (90° azimuth). We are interested in predicting radiation patterns for mining explosion-generated R_g as a function of delay fire direction and horizontal spall trajectory. In Figure 3, we varied the eject angle from 0° (from vertical) to 90° in 15° increments. When the eject angle is 0° , there is no horizontal spall component and the blast is analogous to a fragmentation shot. For quarry blasts, there is some material cast into the pit at eject angles greater than 45° , however, a additional amount of the spalled material is cast into the air at angles between 0 and 30° . Finally, for cast blasts, the majority of the material is ejected at angles greater than 30° . As shown in Figure 3, cast blasts will have the largest deviation from an isotropic source (i.e., a fragmentation blast) with the magnitude of the azimuthal variations being dependent upon the eject angle. In all cases, there is a slight increase in the amplitudes in the direction of the delay-firing. For the cast blasts to take on a more di-polar ("peanut-shaped") radiation pattern, the mass of the horizontal spall must be increased. This plot is meant as an example of the different radiation patterns that can be expected from simple mining explosions (single row without complicated detonation schemes). By adding additional rows of explosives with different interrow and interhole delays, the characteristics can become markedly different.

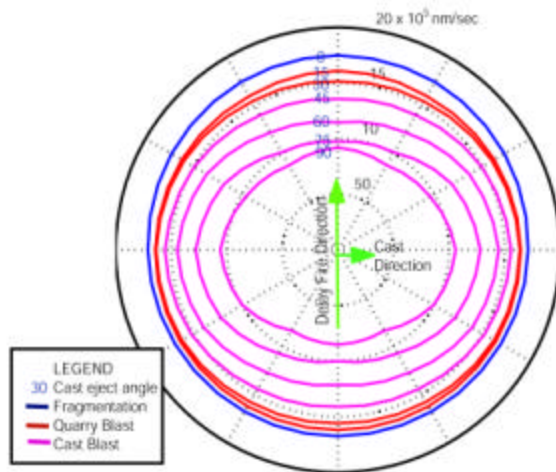


Figure 3. Model results showing azimuthal radiation patterns in R_g amplitudes as a function of spall eject angles for simplified mining explosions. The color scheme highlights typical spall eject angles that can be expected for fragmentation, quarry, and cast blasts. Quarry blasts have components of both fragmentation blasts (efficient fracture of the material) and cast blasts (throwing the rock into the open pit).

Rg Observations

Cast Blasts. We acquired a data set of local and regional recordings of explosions at a large coal mine in northern Arizona (Figure 4). The local recordings were obtained on 24-25 March 1999, when two ~1.6 million pound cast blasts were detonated in a pit (Figure 5) near Kayenta, AZ. Near-source recordings of seismic, acoustic, and videographic data were acquired.

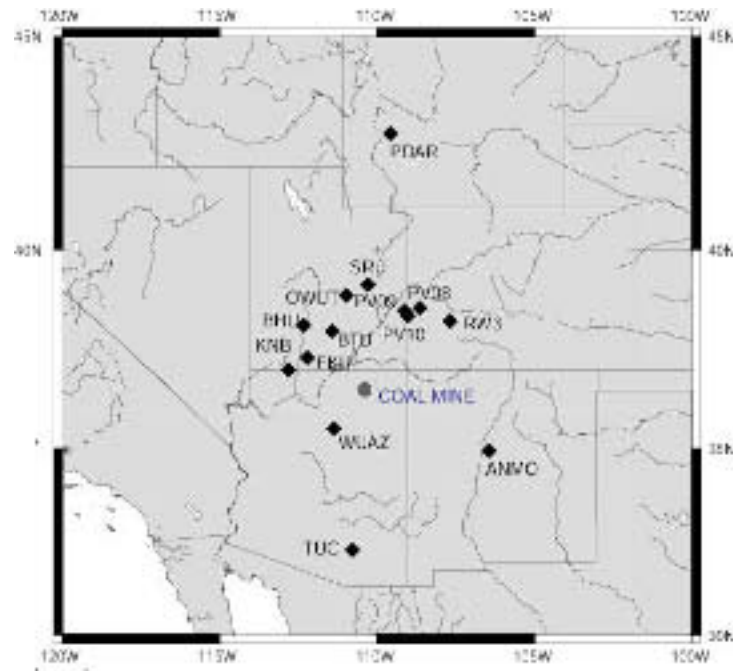


Figure 4. Location of the coal mine in northern Arizona and regional stations that recorded Rg.

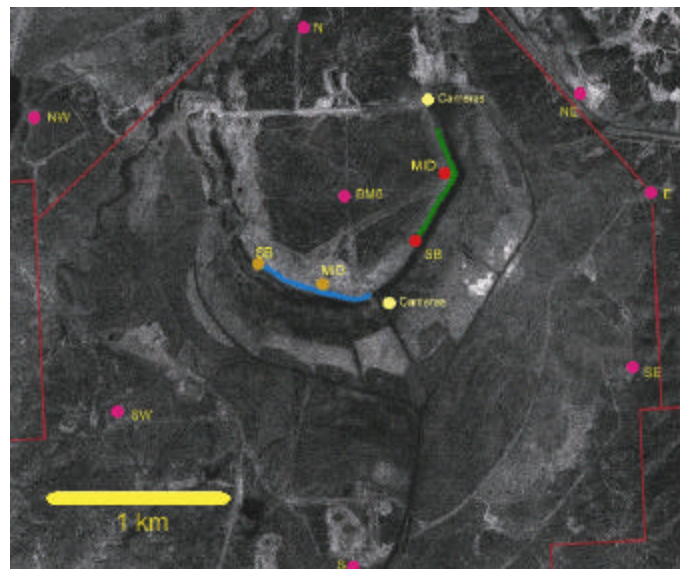


Figure 5. The locations of the seismic recording sites of the cast blast experiment for the 24 March 99 (Green) and 25 March 99 (Blue line) cast blasts. Each event was fired from station SB toward the station MID.

Our focus thus far has been on studying surface wave generation from these two cast blasts, given the uniqueness of the dataset. First, both cast blasts were of approximately the same total yield (1.6 million pounds) and had a similar blasting design (delay times, explosives per delay, burden, depth of charge, etc). The blasts were detonated in the same pit resulting in less than 1 km difference between the locations of the first hole detonations. And finally, because of the semi-circular nature of the pit, a feature unique to the operations at this mine, the orientations of the blasts were approximately perpendicular to each other, thus allowing for relative amplitude comparisons of the two blasts at local and regional distances.

We completed analysis of the regional R_g phase recorded by 17 seismic stations ranging from 135 km to 699 km from the blasts (four examples are shown in Figure 6). The two cast blasts generated R_g dominated by 4 seconds-period that was recorded at relatively great distances as a result of efficient propagation in the Colorado Plateau. The four seconds period corresponds to the approximate total duration of the horizontal spall impact on the pit floor. Figure 7 shows the results

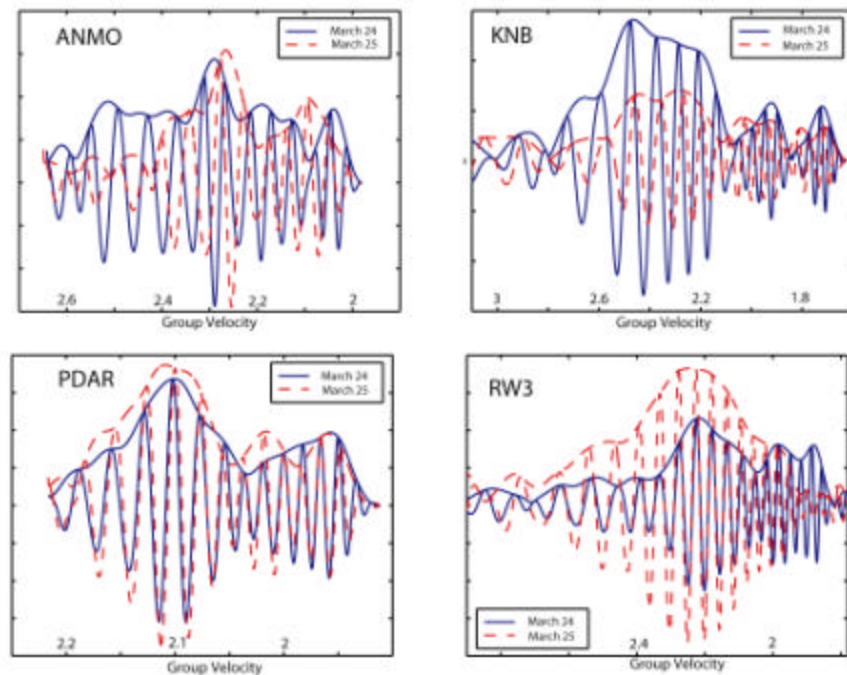


Figure 6. Regional R_g recorded at ANMO, KNB, PDAR, and RW3 for two cast blasts (blue=24 March 1999 and red=25 March 1999) of similar yield (1.6 million pounds of explosives). Differences in the R_g amplitudes can be attributed to radiation patterns for the two blasts that are oriented perpendicular to one another as shown in Figure 5.

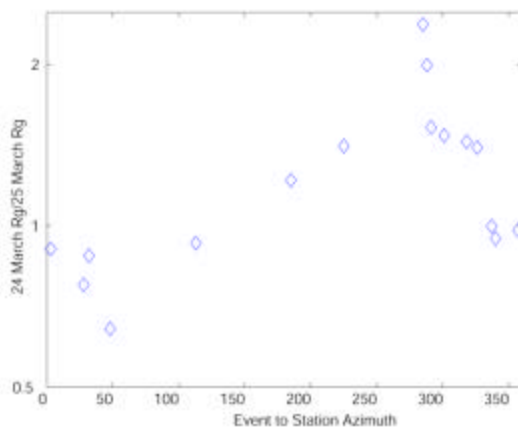


Figure 7. Ratio of the R_g amplitudes for the 24 March 1999 cast blast to the 25 March event.

for all stations and suggests that significant radiation patterns for the two blasts are functions of the orientation of the explosions. The *P* and *Lg* phases did not show the same radiation patterns for these two blasts.

We again used MineSeis1.1 to model these explosions in an attempt to explain the *Rg* observations. We combined seismic velocities measured during the experiment with videographic data to accurately represent the source and spall parameters (Table 2). We generated single-point seismograms using these data and convolved them with Green's functions generated by the reflectivity method (Muller, 1985) for the Colorado Plateau crustal structure. We then convolved these data with comb functions that represent the timing pattern and yield of the individual explosions to represent the superposition seismogram at regional distances. Figure 8 shows the results of using this model to synthesize seismograms for a cast blast as recorded at WUAZ. The model adequately predicts a significant portion of the *Rg* wave packet.

Parameter	Value
Explosive Depth	30 m
Burden	5 m
Face Azimuth	0 (24 March) 90 (25 March)
P-wave Velocity at Depth	7.9
Spall Impact Pulse Width	2
Spall Initiation Pulse Width	1
Spall Yield	22 kT
Yield per hole	8131 kg
Eject Angle	70°
Vertical Falling Distance	30 m
Spacing Between Rows	10 m
Receiver Distance	134.7
Receiver Azimuth	0:15:360
Intershot Delay	17 ms
Interrow Delay	150, 100, 150, 150, 150
Number of Rows	5
Number of Holes per Row	88

Table 2. Source parameters used to model the northern Arizona cast blasts.

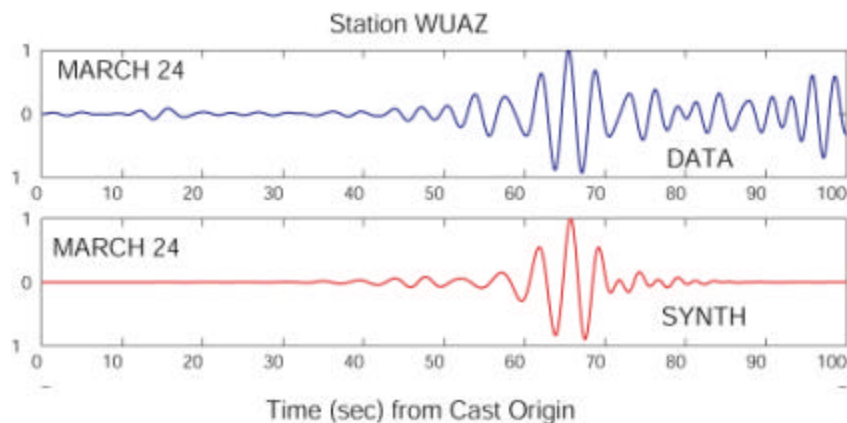


Figure 8. Observed (blue) vs. synthetic (red) cast blast seismograms as recorded at WUAZ. Both the observed and synthetic data are normalized with respect to the largest amplitudes.

The left panel of Figure 9 shows the theoretical surface wave amplitudes as a function of azimuth for the two cast blasts. The radiation patterns are not isotropic, as is the case when only vertical spall is modelled (Figure 3), and show larger amplitude lobes perpendicular to the bench, with a relative enhancement noted for the direction of the delay firing (the arrows shown in the center of the plot). The overall effect of the horizontal spall is to create amplitudes as much as approximately four times greater in the direction normal to the bench than parallel to the free face. The ratio of the amplitudes from the two theoretical radiation patterns is presented in the right panel of Figure 9, and the R_g amplitude ratios (March 24 R_g /March 25 R_g) measured from the regional data are overlain on the plot (red circles). The observed data do support the radiation patterns predicted from the modeling. However, more data are needed to confirm the results, and this study would benefit greatly from stations due east and south of the cast blasts. We are searching for additional data from stations that were not obtained from the USGS AutoDRM during the initial search.

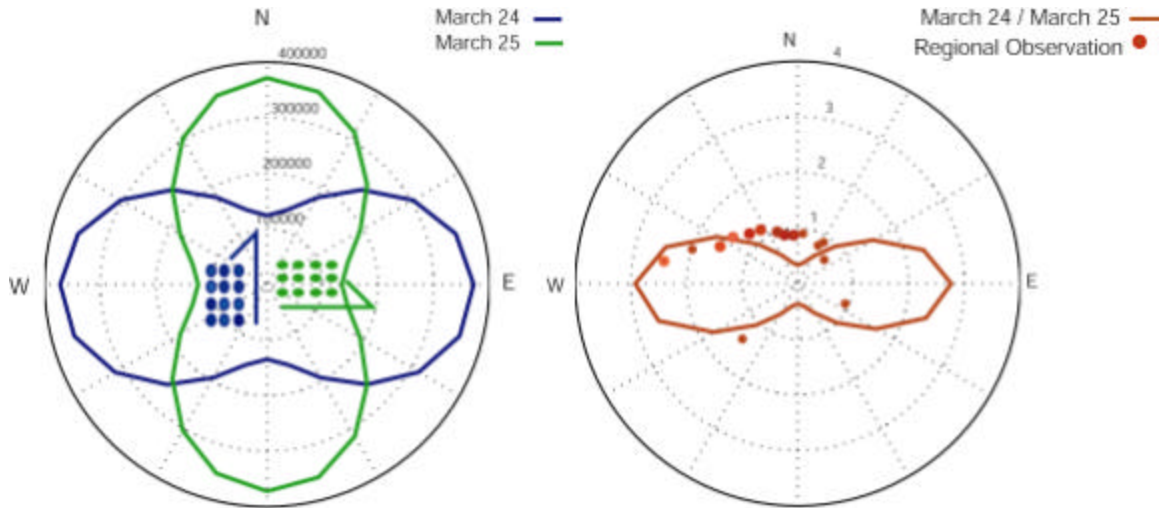


Figure 9. (Left) Radiation patterns for R_g based upon model data recorded at regional distances for two identical cast blasts oriented perpendicular to each other. The delay firing direction is shown by the arrow that is parallel to the bench, thus perpendicular to horizontal spall. (Right) Ratio of the two radiation patterns compared with actual data (red circles) recorded at varying azimuths to the coal mine.

Quarry Blasts. Bonner *et al.* (1994) documented azimuthal R_g radiation patterns for quarry blasts in Central Texas. They found that R_g amplitudes are enhanced for (1) paths that do not travel through the quarry pit and (2) paths in the direction of the delay firing. Figure 10 shows the data from one of these quarry blasts, and the radiation pattern does not resemble closely any of the patterns in Figure 3. In a previous modeling study (Barker *et al.*, 1997), three-dimensional finite difference calculations and wavenumber integration synthetics were used to interpret near-regional azimuthal variations from quarry blasts in Central Texas. The observational data were compared to the synthetics in relation to the effects of local quarry topography and the spall of the material from the quarry face. The simple explosion plus spall model of Barker *et al.* (1993) predicted the observations better than 3-D finite-difference calculations, however, discrepancies existed between both models and the observations. We plan to further investigate this dataset in the upcoming stages of the project.

Fragmentation Blasts. We have only recently received the detailed blasting records for fragmentation shots at a copper mine in the southwestern United States. We have already downloaded data from 25 shots from this mine as recorded at three to six regional stations. We will use the shot information to perform modeling of fragmentation blasts.

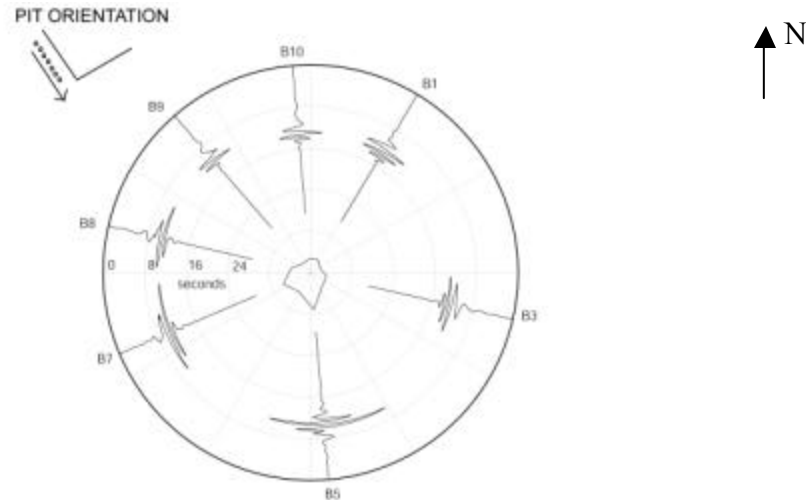


Figure 10. Observed R_g amplitudes from a quarry blast in central Texas (Bonner et al., 1996). Amplitudes for paths that do not traverse the quarry pit as well as paths in the direction of the delay-firing are enhanced.

3-D Modeling of Short-Period Surface Waves

We used a numerical wave field modeling method to generate Green's functions for a 3-D earth model consisting of the northern Colorado plateau, the Uinta Basin, the middle Rocky mountains including the Uinta Mountains, and western Wyoming. The velocity model regionalization was based upon the work of Keller *et al.* (1976) and Prodehl and Lipman (1989). The 3D model was constructed on a 0.5×0.5 degree grid and from 35°N to 44°N from 112°W to 107°W with the velocity profile at each point consisting of a 6 layer crust over a 200 km mantle half-space. Numerical methods allow the incorporation of realistic structural features, such as strong lateral velocity variations, anelastic attenuation and surface topography, that affect the propagation of short period surface waves. The particular modeling method we propose to use, called the Generalized Fourier Method (GFM), was developed specifically for regional wave propagation studies (Orrey and Robinson, 2001). Preliminary results of the GFM synthesis of explosion-generated surface waves for our model are presented in Figure 11. For the next phase of this research, we propose to combine the MineSeis code of Yang (1998) with the GFM code of Orrey and Robinson (2001) to model explosions in regional 3-D media.

CONCLUSIONS AND RECOMMENDATIONS

The database we have assembled for this study is unique in its content of local and regional recordings of various classifications of explosions. We have detailed source information from the blasters and in some cases videographic data to help ascertain the physical processes at work during the explosions. We have used the explosion-generated R_g to determine upper crust velocity models and attenuation values for the study regions, and will use this information during the upcoming modeling study. During Phase II of the project, we propose to expand the modeling effort to include complex source models and propagation in 3-D media using Fourier pseudo-spectral approximation (Orrey *et al.*, 2001). Finally, we have empirical and modeling results that suggest cast blast discriminants can be developed based upon radiation patterns of R_g , and we will attempt to transport them to additional datasets during the remainder of the research project.

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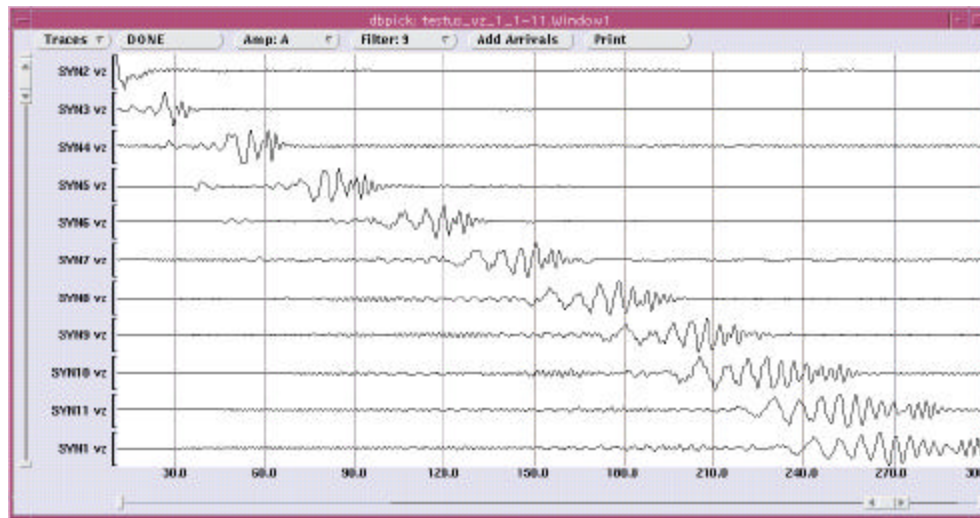


Figure 11. Preliminary results for modeling explosion generated short-period surface waves in a 3-D model developed for the middle Rocky Mountains, Uinta Basin, and Colorado Plateau. Each trace is a vertical velocity time series separated by 10 km with the last trace representing PDAR data.

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